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6. AUTHOR(S)

Paul R. Prucnal

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Dept. of Electrical Engineering
Princeton University
Princeton, NJ 08544

8. PERFORMING ORGANIZATION REPORT NUMBER

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AFOSR/NE Attn: Dr. Alan Craig
801 North Randolph Street, Room 732
Arlington, VA 22203-1977

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We have proposed a new MAC protocol, which possesses desirable characteristics: it provides a low latency delay as in ALOHA random access protocol under light traffic, and attains the achievable maximum throughput like the TDMA protocol, as the traffic load increases. What is significant is that the proposed protocol is superior to both I TDMA and I-SA protocols throughout the entire range of traffic level. This advantage is achieved because of the extra information that the network users can receive through the control channel. Therefore, the proposed MAC protocol is capable of changing the access mode gradually from the random access mode to the scheduled mode, as the traffic level increases, and this adaptive capability is attained due to the additional network resources, i.e., the control channel and the transmitter and receiver at each user node that can communicate over the control channel.

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FRI-BMDO: Terabit Per Second Networks and Devices for Data Fusion

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Sent to:

Wendy M. Veon
AFOSR/PKC
801 N Randolph St Room 732
Arlington VA 22203-1977

Contract #: F49620-95-1-0532
Contractor: Princeton University

AFOSR BBA 94-6

Principle investigator:
Paul R. Prucnal
(609) 258-5549
(609) 258-2158 (Fax)

Co-PIs:
Stephen R. Forrest
(609) 258-4532
(609) 258-1954 (Fax)
Hisashi Kobayashi
(609) 258-1984
(609) 258-2158 (Fax)
Warren S. Warren
(609) 258-4271
(609) 258-6746 (Fax)

1 Objectives

The objective of this research is to develop and demonstrate an optical network architecture which offers both ultra-high speed and ultra-high parallelism, allowing the transfer of image data at Tb/s rates. The network architecture will provide both broadcasting capability and low data-transfer latency, which will facilitate fusion processing. This architecture will be based on several novel optical and optoelectronic technologies and processing algorithms which we propose to investigate, which push the fundamental limits of both the speed and parallelism of optics:

- Spectral encoding of femtosecond optical pulses, in which ten-thousand orthogonal wavelength channels can each be modulated at MHz rates;
- All-optical time-division multiplexing and demultiplexing of picosecond optical pulses, allowing serial data transmission at speeds approaching a Tb/s;
- Thin film implementations of encoders, wavelength-channel-dropping filters, and detector arrays based on highly parallel optoelectronic integrated circuits.
- Algorithms for optical CDMA and data correlation for fusion processing.

These key technologies will enable an optical network architecture based on a hybrid combination of wavelength-, time- and code-division multiplexing, with rapid channel access and several Tb/s aggregate-throughput. These multiplexing formats adapt to data fusion applications in a natural way, in that entire images can be encoded in parallel- each pixel or voxel on a distinct wavelength within a sub-nanosecond time slot. Many such time-slots, each containing an image, can be time-interleaved and broadcast through a shared optical medium such as an optical star, and demultiplexed using ultrafast optical TDM. Individual images, or sets of images, can then be rapidly selected (using, for example, a reservation-ALOHA protocol,) and demultiplexed at the receiver array. In this way, vast amounts of data can be shared and processed simultaneously, which is desirable for data fusion applications.

Our proposed system uses the novel features of AOM pulse shaping, terahertz optical asymmetric demultiplexing, and other techniques to spectrally encode and decode data at >1 Tb/s. The acousto-optic device we use as an optical correlator is rapidly tunable, and can process analog as well as digital signals. (This is in contrast to other femtosecond pulse shaping techniques using LCD modulators, which are neither fast nor can process analog signals.) Our device is well suited, for example, to optical feature recognition in 2-D analog images. In essence, we use spatial-temporal dispersion and a combination of WDMA and TDMA to divide this huge bandwidth into manageable channels, while practically eliminating problems from dispersion. Individual ultrafast (<100 fs) input laser pulses give 1250 different wavelength components, each of which can be encoded independently with an AOM. The resulting pulse will in general be longer than the input pulse, and can be as long as 200 ps. This defines the length of the "time slot" ; another completely independent pulse can be transmitted on the network in the next slot. Partitioning into different wavelength channels can be done differently for each time slot, thus giving compatibility with a wide range of data rates. While some device development is proposed (largely to reduce complexity and size), this system can be built with existing commercial components. Data fusion processing will be supported by this novel network architecture in several fundamental ways. First, our ultra-dense WDM/TDM multiplexing scheme will provide a high degree of parallelism in the network, providing simultaneous data transfer, from thousands of sensors. This, in turn, will allow cross-correlation of multiple sensor inputs. The optically-processed CDMA access scheme will allow rapid channel access and sensor input filtering with low latency. The elimination of multiple access protocols removes the primary latency bottleneck in the network. CDMA also provides simultaneous asynchronous access, allowing rapid reconfigurability of the interconnections. In this way, the network can rapidly adapt to changes in the environment being sensed, focusing, for example, on one subset of sensors while observing the remainder of the sensors only peripherally. Handling the vast amounts of data will be assisted by preprocessing in the optical domain, including data compression and correlation. In particular, the novel optical technology we develop for CDMA encoding and decoding will also allow optical correlation and filtering of sensor data. Finally, the Terahertz bandwidth offered by this network will allow transfer of broadband data such as high-resolution video. Together, the novel features of this Terahertz network architecture will accomplish optical preprocessing and correlation of data, feedback and filtering to and from, for example, sensors, and adaptation of the network to a changing environment.

2 Approaches

The awarded three year program was intended to design and demonstrate an optical network architecture which offers both ultra-high speed and ultra-high parallelism, facilitating data fusion processing at Tb/s rates. This architecture is based on several novel optical and optoelectronic technologies and processing algorithms which we propose to investigate, which push the fundamental limits of both the speed and parallelism of optics. The work can be divided into four main tasks including spectral encoding of femtosecond optical pulses, all-optical TDM network architectures, thin-film implementations of the encoders and decoders, and algorithms for optical CDMA and data correlation for fusion processing, as described below:

1. Spectral encoding of femtosecond optical pulses
   (a) Demonstrate binary amplitude modulation of 100 fs laser pulses to >1000 different frequency components using existing acousto-optic modulators and grating dispersion.
   (b) Develop a **prototype communications network** between the Chemistry and Engineering buildings (distance 300 m) which will support Ethernet communications, using only one 200 ps time slice every 1.25 μsec. This will serve as a proof of principle for 6000 Ethernet channels on a single fiber.
   (c) Design and test high-finesse interferometers and advanced (thin film) acousto-optic modulators to reduce complexity and cost.
2. All-optical time-division multiplexing and demultiplexing of picosecond optical pulses
   (a) Perform system design and analysis for hybrid network architecture;
   (b) Demonstrate operation of Terahertz Optical Asymmetric Demultiplexer with multiple wavelengths;
   (c) Demonstrate hybrid TDM/WDM network node operation;
   (d) Demonstrate hybrid TDM/CDM network node operation.

3. Thin film implementations of encoders and wavelength-channel-dropping filters

   (a) Model thin film implementations of the optical modulator using guided wave algorithms; use methane/oxygen reactive ion etching of InGaAsP to demonstrate and test in-plane lens operation; grow, using gas source molecular beam epitaxy, semiconductor optical amplifier structure which forms the base technology for the tunable channel dropping filters.

   (b) Characterize propagation in the in-plane lens structures, and compare with modeling results; update models to optimize lens designs; demonstrate sputter-deposited SAW acousto-optic modulators for thin film MUX element; fabricate DFB-type semiconductor optical amplifier for the channel dropping filters using e-beam written, 1/4 shifted gratings.

   (c) Integrate AO modulator and in-plane, etched lenses to demonstrate optical multiplexing function in a monolithic device. Fully characterize device operation to understand how to optimize future models; fabricate full channel dropping filter based on the DFB/optical amplifier technology developed in years 1 and 2.

4. Design an optical TDM/CDMA network and develop fusion processing algorithms to be supported by the network

   (a) Construct a set of signature sequences (or signals) for CDMA networks applicable to different data fusion applications; conduct performance analysis of the CDMA networks, and calculate the "processing" gain, and the signal-to-noise ratio at the receiver output.

   (b) Derive a set of data fusion processing algorithms (filtering, pattern matching, etc.) applicable at both the signature demodulation stage, and the data decoding (or demodulation) stage.

   (c) Validate the network architecture and design based on experimental results to be obtained from our planned prototype TDM/WDMA and TDM/CDMA networks; validate data fusion processing algorithms based on our optical data fusion prototype.

3 Accomplishments

3.1 Spectral Domain CDMA for a Coherent Optical Network

A major feature of the proposed network architecture is to build CDMA on top of TDM/WDMA (i.e., TDM/WDM/CDMA) or replace WDM by CDMA (i.e., TDM/CDMA).

3.1.1 Duality between Time-domain and Spectral-domain

One of the first objectives in this study was to clarify relationships that exist between the time-domain CDMA and the spectral-domain CDMA. The former has been reasonably well understood and devloped, and has been actually used in RF networks, originally in military communications, and more recently in a a number of spread-spectrum based LANs in the ISM (industrial, scientific and medical) spectrum band. One of the most exciting developments we witness today is use of direct sequence spread spectrum adopted in the IS-95 (Interim Standard 95 of the EIA/TIA) which

Time-Domain	Spectral Domain
TDM	WDM
FDM	TDM
FDM/TDM	TDM/WDM
Long pulse	Broad Spectrum
Narrow spectrum	Short pulse
Time encoding	Spectral encoding
Spread-spectrum signal	Spread-time signal
Correlator in time	Correlator in spectrum
Delay of a "chip"	Shift of a "bin"
Matched filtering in time	Matched filtering in spectrum

Table 1: Duality between the time-domain and the spectral-domain

is the North America CDMA Standard for digital cellular network. The emerging satellite PCS (personal communication services) will be built on a world-wide cellular network based on LEO (low earth orbiting) satellites, and many of the planned Big LEO systems will use CDMA.

The spectral-domain CDMA, on the other hand, is still in the conceptual stage, and a very few studies have been reported. Table 1 shows the mathematical relationships that exist between the time-domain and the spectral-domain.

If we translate the relationships summarized in Table 1 into the CDMA in the two different domains, we will obtain the duality relations that are illustrated in Figure 1.

3.1.2 Examples of CDMA spectral encoding

In this subsection we report a summary of our preliminary results on numerical evaluations of CDMA spectral encoding. [1]

In Figure 2 the solid curve shows the envelope of spread-time signal–on the order of several hundred femto seconds (fs) to one pico second (ps)–, when 10 THz flat spectrum (which corresponds to a pulse of duration on the order of 100 fs) is spectral encoded by a 7-bit M sequence $[+--++---]$. The dashed curve represents the envelope of the uncoded pulse, whose shape is the well known sinc function. We confirm that the pulse width is indeed on the order of 100 fs. Figure 3.1.2 shows similar curves, when an eight-bit Hadamard-Walsh function $[+--+-++-]$ is used for the spectral encoding. The dashed curve is again the uncoded pulse, and the solid curve is the spread-time signal. Because the Hadamard-Walsh (H-W) sequence contain an equal number (which is four in this case) of $+$'s and $-$'s, the corresponding time signal takes on zero at $t = 0$. The M sequence contains one more $-$ than the number of $+$'s, the spread-time signal takes on $1/M$ at $t = 0$, and Figure 2 verifies this simple observation. Figures 2 and 3.1.2 illustrates some difference in detail shapes of the time-spread signal waveforms. The M-sequence encoded pulse shows an almost continuous envelope, whereas the H-W sequence encoded pulse shows its "side-robes" as sharp pulses as narrow as the original uncoded pulse. But this difference in the shape of spurious peaks does not seem a reflection of M-sequence versus H-W sequence, but is a result of the difference in the sequence lengths (i.e., 7 vs. 8).

If we increase the size of encoding sequence, and use an M sequence of length 127, then the

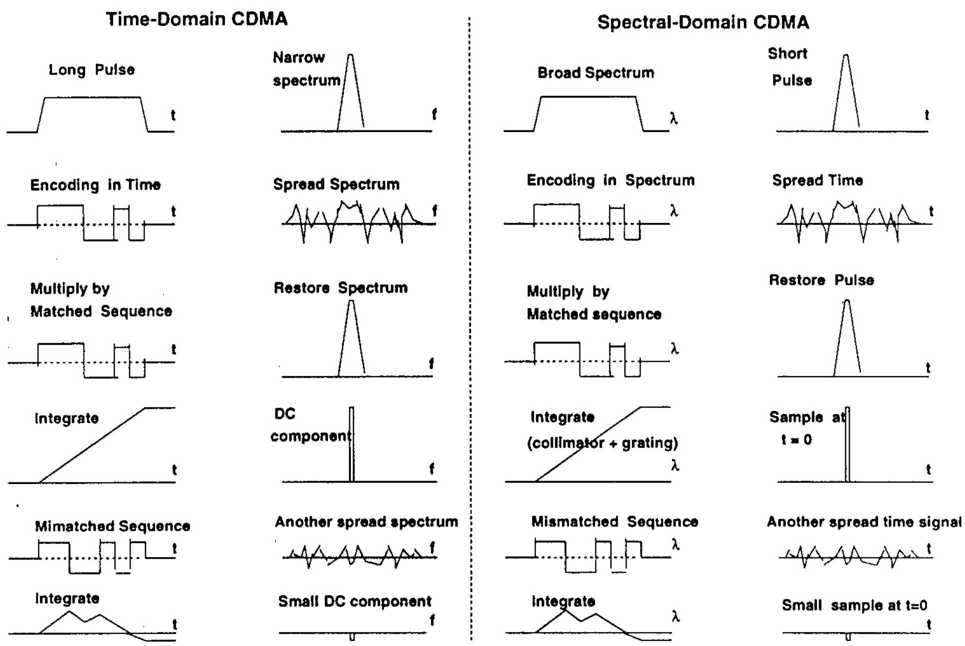

Figure 1: Duality between the time-domain CDMA and the spectral-domain CDMA

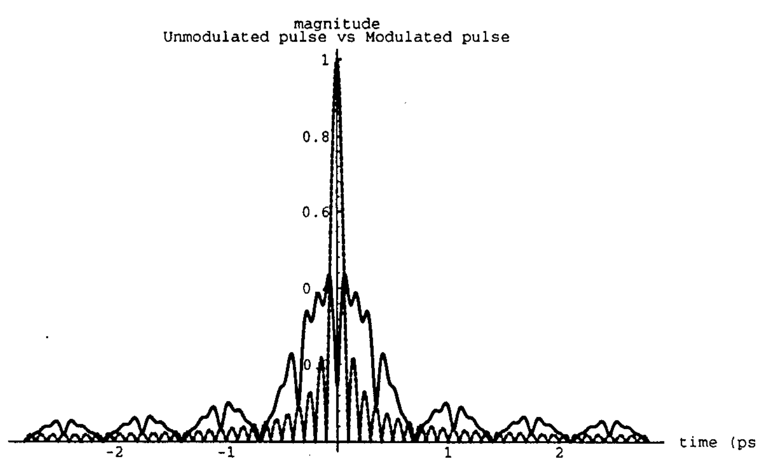

Figure 2: Uncoded pulse (dashed curve) with 10 THz flat spectrum, and the spread-time signal (solid curve), encoded by a 7-bit M sequence

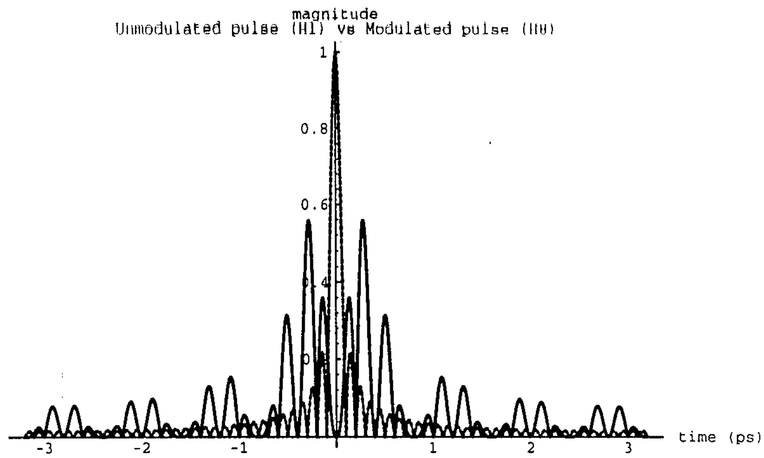

Figure 3: Uncoded pulse (dashed curve) with 10 THz flat spectrum, and the spread-time signal (solid curve), encoded by an 8-bit H-W sequence

corresponding time-spread signal is shown in Figure 4 Since the spreading factor is now 127, the encoded signal is spread in time on the order of 100 fs $\times 127 = 12.7$ ps. One conspicuous feature of this plot is that the spread-time signal has side robes whose amplitudes change according to another sinc function. Although this behavior was not foreseen before the analysis, it is explainable by noting that the spectrally encoded signal can be mathematically constructed as outlined below.

3.1.3 Characterization of the spread-time signals

In order to understand the time signal behavior exhibited in Figure 4, we represent the spectral encoding mathematically as follows. Figure 5 shows an illustrative example of the M sequence of length seven used in Figure 2: (a) is a periodic impulse sequence in the spectral domain; (b) is a frequency "bin" (i.e., the spectral counterpart of a "chip" in the time domain CDMA); (c) is the convolution in the spectral domain; (d) is the flat spectrum of 10 THz, i.e., uncoded pulse spectrum; and (e) is the encoded spectrum. The Fourier transform of the periodic impulse sequence is also a periodic impulse sequence. The convolution between (a) and (b) in the spectral domain corresponds to a multiplication in the time domain. This explains the sinc function envelope of siderobes observed in Figure 4, which is also noticeable, albeit less conspicuously, in both Figures 2 and 3.1.2. In other words, the sinc function envelope observed in the time-spread signal is nothing but the Fourier transform of the frequency bin of Figure 5 (b). Thus the time signal that corresponds to the spectrum (c) is an impulse sequence whose amplitude is modulated by the above sinc function. The time signal of the flat spectrum (d) is the first sinc function envelope we observed in Figures 2 and 3.1.2. Since multiplication in the spectral domain corresponds to convolution in the time-domain, the time signal of the spectrum (e) is the above modulated impulse sequence passed into a bandpass filter whose transfer function is given by (d). Therefore the detailed shape of the time-spread signal (e) has the resolution on the order of 100 fs, i.e., the original uncoded short pulse.

Figure 6 shows an expanded view of the time-spread signal of Figure 4 in the neighborhood of $t = 0$. This confirms the above analysis, namely, the detailed behavior has the time resolution of

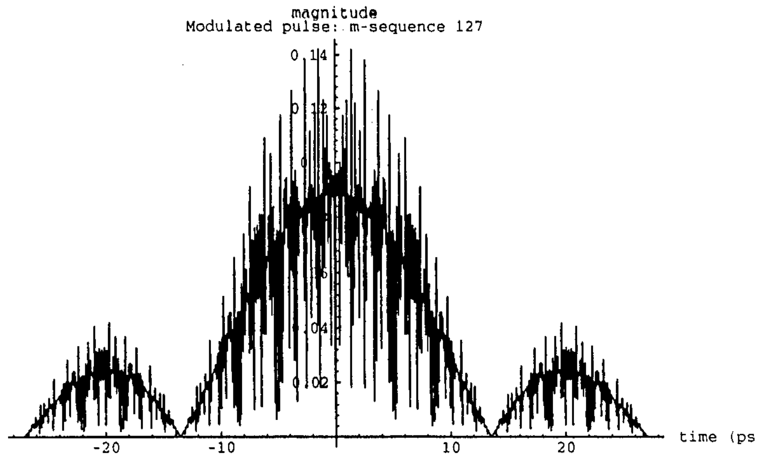

Figure 4: Uncoded pulse (dashed curve) with 10 THz flat spectrum, and the spread-time signal (solid curve), encoded by a 127-bit M sequence

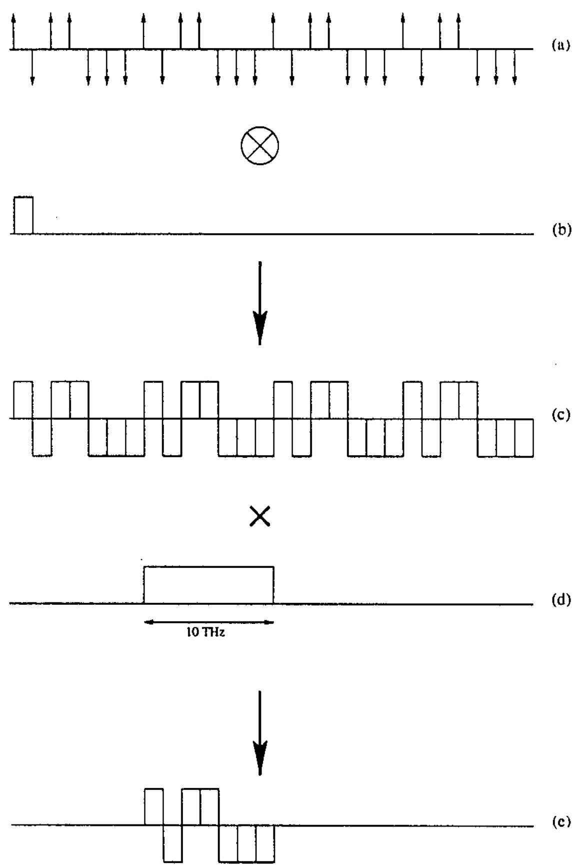

Figure 5: Construction of a spectral encoded signal by applying a convolution and a multiplication to a periodic impulse function

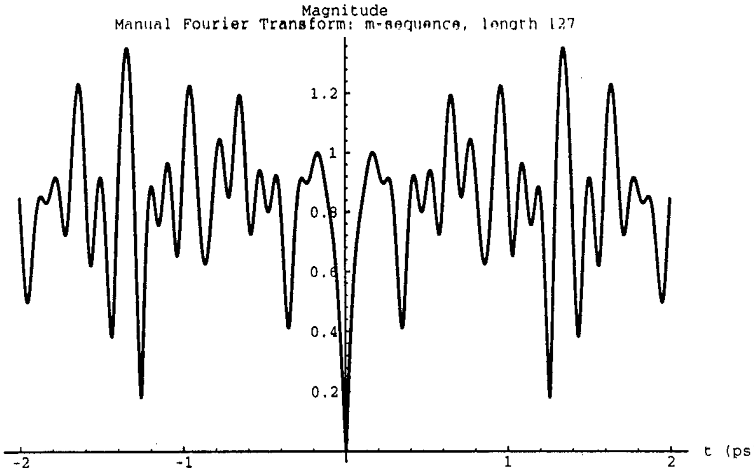

Figure 6: An expanded view of the time-spread signal, as a result of encoding by the M sequence of length 127

100 fs, i.e., the duration of the original uncoded pulse.

3.2 Medium Access Protocols for Optical Star Networks

3.2.1 Background

We have investigated the issue of medium access control (MAC) of the proposed optical network, i.e., how to assign channels among a large number of contending users, under the assumption that the total number of users attached to the network outweighs the number of users that can be simultaneously supported at a given time, and that some applications are packet-switching oriented. If a majority of services are connection-oriented, and the network operates in circuit-switching mode, then the MAC protocol will not be an issue.

There exists a considerable body of the literature on MAC protocols, because that is the most critical component of local area networks (LANs). An optical star coupler we assume for the proposed optical network is a *shared medium* like twisted pair wires or coaxial cables that are most commonly used in today's LANs that run somewhere between 10 Mbps and 100 Mbps. Such a medium possesses both multiple accessing and broadcasting capabilities. Thus, we might be tempted to pursue some type of random access protocols–most notably CSMA (carrier sense multiple access), and CSMA/CD (CSMA with collision detection)–or token passing protocols–such as in a token ring LAN. But these types of protocols are characterized by the channel efficiency S, which takes the following form

$$S = \frac{1}{1 + ka}, \tag{1}$$

where k is some constant on the order of unity, which depends on the specific MAC protocol, and the parameter a is the normalized propagation delay, i.e., the propagation delay D_{prop} divided by the packet (or message) transmission time T_{pkt}:

$$a = \frac{D_{prop}}{T_{pkt}} \tag{2}$$

As an illustrative example, consider an optical network that is connected by a star coupler. If the geographical size of the network is $D = 1000$ [m], the packet size $L = 1000$ [bits], and the transmission rate of an optical channel $R = 10$ [Gps]. Then the normalized propagation delay is given by

$$a = \frac{D/c}{L/R} = \frac{DR}{cL} = \frac{10^3 \cdot 10^9}{3 \times 10^8 \cdot 10^3} \approx 33.3 \gg 1. \tag{3}$$

Even if we assume an extremely small geographical size, such as $D = 100$ [m], the parameter a is larger than one, unless the packet size exceed 3000 [bits]. If the speed of a channel becomes greater than 10 Gps (which is a reasonable assumption to make for the future networks), then that will also increase the parameter a. Therefore it seems essential that we need to explore a better MAC protocol as long as a good portion of applications that run on the proposed network is asynchronous traffic or bursty traffic, for which a static connection setup is inefficient in use of the network resources.

Two MAC protocols recently studied to send data packets in TDMA fashion over a WDM (wavelength-division multiplexed) optical star network are "Interleaved TDMA (I-TDMA)" and "Interleaved Slotted ALOHA (I-SA)" [2].

In I-TDMA, each transmitter has a tunable laser, and tune its wavelength to those of WDMA channels in a cyclic order, whereas the individual receiver is tuned to a fixed wavelength channel. Thus, I-TDMA can be viewed as an extension of the synchronous TDM, as far as slot assignment is concerned, and hence it suffers from the inherent disadvantage of the synchronous TDM scheme: if the assigned transmitter has nothing to send, the assigned slot is wasted; and the expected latency is one half of the frame period.

In I-SA, the time assigned to a specific receiver, say User i, has multiple slots per frame period, and these slots are accessed by those who wish to send packets to User i by slotted ALOHA protocol. Hence the main characteristics of I-SA are essentially those of slotted ALOHA: achievable channel efficiency is low (i.e., $e^{-1} = 0.36$), and as the traffic load increases, collisions and retransmissions dominate the channel usage, hence the average delay may become excessively large.

3.2.2 Proposed MAC Protocol

We propose a new MAC protocol, which is a hybrid of I-TDMA and slotted ALOHA, but is superior to both over the entire range of traffic load. In this scheme, we divide also the time axis associated with a given receiver channel into a sequence of frames. Each frame, called a "channel frame", is divided into slots, and the assignment of the slots are done as in I-TDMA. If the transmitter which is scheduled for a given slot has nothing to send, then this slot should not be left unused as in I-TDMA. Both channel efficiency and transmission delay can be improved if this slot can be used by some other transmitter that has a packet to send to the receiver of this channel.

In order to accomplish such improvement the following two conditions must be met: (i) the other transmitters must be informed of the availability of this slot that was not scheduled to them; (ii) if multiple transmitters wish to send packets in this slot, the contention must be resolved. For these purpose a *control channel* must be created by setting aside some frequency band, and each user must be provided the capability to transmit and receive control information over this channel. A control channel's frame contains M slots of C bits each, where M and C are the number of users and the number of wavelength channels.If user m $(0 \leq m \leq M-1)$ has a packet to send in its scheduled slot of using channel c $(0 \leq c \leq C-1)$, then the c-th bit of the m-th time slot in the control channel should be set "1", and "0" otherwise. Thus, a bit tuned to "1" in the control channel serves as a reservation confirmation bit.

Whenever a transmitter sees "0" in the c-th bit in some slot of the control channel, it may attempt a packet transmission if it has a packet to send over the channel c. When a collision occurs, then a retransmission must be attempted after some delay as in slotted ALOHA.

3.2.3 Performance of the proposed protocol

It is not difficult to see that this new protocol should behave like I-TDMA under heavy traffic load, since the users will be most likely to use the scheduled slots, and slots will be rarely made available for unscheduled users. Similarly the new MAC protocol approach I-SA under light traffic condition.

Figure 8 shows a simulation result, which compares the proposed protocol and I-SA in terms of "packet delay versus network throughput", where the variables in the legend are: C = the number of wavelength channels; M = the number of users in the network; Q = the buffer capacity of each transmitter [packets]; and ν = the probability of retransmission per available slot. We see that for

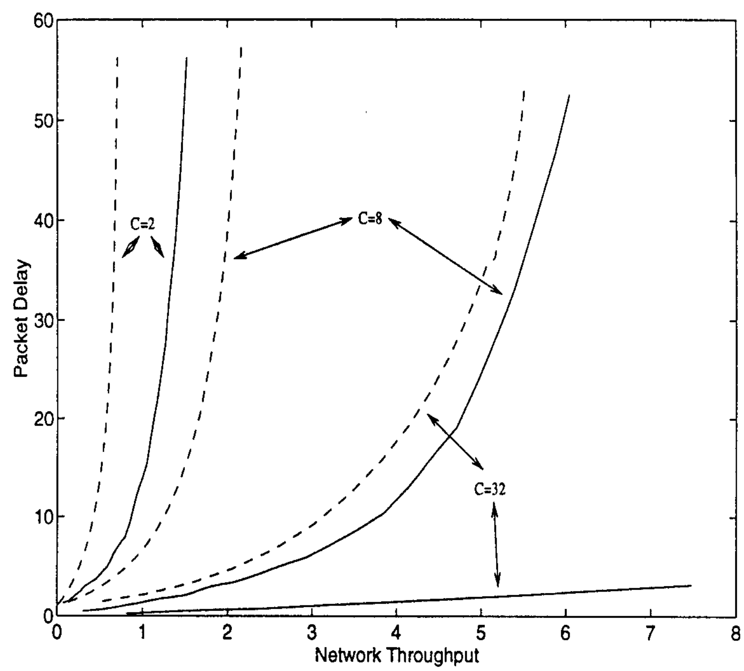

Figure 7: Performance comparison of the proposed protocol (solid curves) and I-SA (dashed curves), $M = 32$, $Q = 10$, $\nu = 0.05$.

the entire range of network throughput, the mean packet delay is smaller for the proposed protocol than for I-SA. The achievable throughput is greater for the proposed protocol, than that for I-SA, which is bounded by $e^{-1}C = 0.36C$.

Figure ?? shows a similar comparison between I-TDMA and the proposed protocol. The system parameters chosen is the same as those used in Figure 8. The proposed protocol is found to be superior to I-TDMA in terms of the mean packet delay under light traffic: the minimum packet delay for I-TDMA is the latency delay, which is one half of the frame interval, or $M/2$ [time slots].

In order to better illustrate the performance of the proposed protocol, we break the throughput

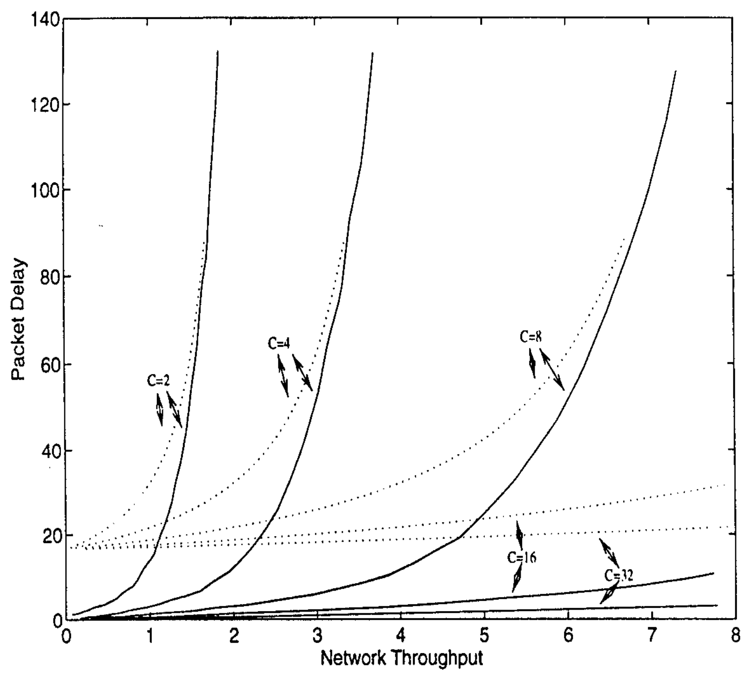

Figure 8: Performance comparison of the proposed protocol (solid curves) and I-TDMA (dashed curves), $M = 32$, $Q = 10$, $\nu = 0.05$.

into two parts: one part due to packets sent a la slotted ALOHA, using slots freed up, and the other part due to packets sent in preassigned slots. Figure ?? shows these two components as functions of the packet generation rate λ [packets/slot] per user. It is clear that under light traffic the ALOHA type transmission dominates, and as the traffic load increases, packet transmission by TDMA becomes dominant.

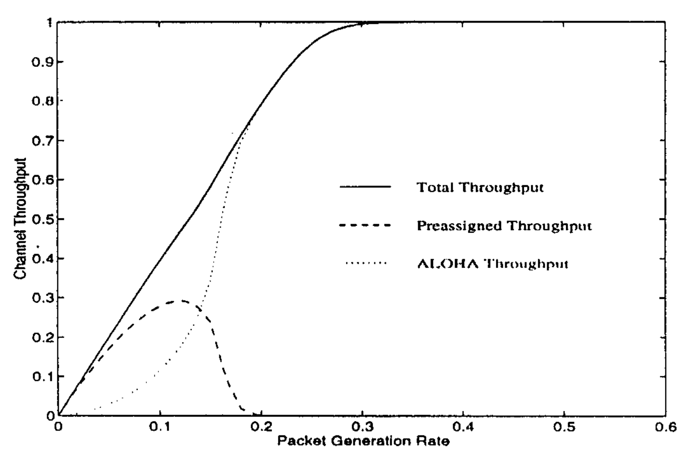

Figure 9: Breakdown of the total throughput into two components

Conclusion

We have proposed a new MAC protocol, which possesses desirable characteristics: it provides a low latency delay as in ALOHA random access protocol under light traffic, and attains the achievable maximum throughput like the TDMA protocol, as the traffic load increases. What is significant is that the proposed protocol is superior to both I TDMA and I-SA protocols throughout the entire range of traffic level. This advantage is achieved because of the extra information that the network users can receive through the control channel. Therefore, the proposed MAC protocol is capable of changing the access mode gradually from the random access mode to the scheduled mode, as the traffic level increases, and this adaptive capability is attained due to the additional network resources, i.e., the control channel and the transmitter and receiver at each user node that can communicate over the control channel.

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3. 3 Optical packet compressor operating at 100 Gb/s

In the development of optical time division multiplexing (OTDM) systems at near terabit/sec rates, novel subsystems are required that utilize both fiber and integrated optics. One such subsystem is a tunable delay line, where electrooptic switches or pairs of modulators are cascaded with precise delays such that optical path lengths may be selected electrically. Tunable delays have been integrated in semiconductor [1] and silica [2] waveguides, as well as with fiber delays. While integrated delays have the advantage of lithographically defined precision, they are generally limited to lengths less than one or two cm.

An optical packet compressor is a type of delay line requiring differential delays of several meters [3]. This structure, shown in figure 1, consists of periodically modulated switches and passive recombiners to compress an optical packet encoded by a slow data source (e.g. 100 Mb/s electronics) into denser packets (e.g. 100 Gb/s) for optical packet-switched asynchronous transfer mode (ATM) networks.

A packet compressor consists of $\log_2(N)$ compressor stages, where N is the number of bits per packet. Each stage consists of fiber pairs having differential lengths corresponding to optical travel times of T-t, 2(T-t), 4(T-t), . . . 2^{n-1}(T-t), where T is the incoming bit period and t is the outgoing bit period, with either a modulator in each fiber segment or a switch between each stage. The modulators or switches are clocked such that after the first stage, bits are paired in time; after the second stage, bits are compressed in groups of four, etc., until the entire packet is compressed.

The reliable and reproducible cleaving and splicing of such fiber stages to the tolerances required for 100 Gb/s multiplexing pose a significant manufacturing challenge, especially with the long differential fiber lengths required at the later stages. For example, in a full 9-stage packet compressor needed for an ATM packet with an incoming data rate of $1/T$ = 1 Gb/s, the 9^{th} stage would require a differential fiber length over 50 m with a tolerance of ±200 μm (for ±1 ps accuracy).

We have constructed a 3-stage eight bit compressor which compresses 100 Mb/s packets to a 100 Gb/s using 2x2 $LiNbO_3$ cross-bar switches, polarization maintaining fiber, polarization maintaining couplers, as shown in Figure 1. Figure 2 illustrates the timing of the bits at each stage as they are appropriately delayed to travel first in pairs, then in quadruplets, and finally as a compressed eight-bit 100 Gb/s packet.

Figure 3 shows an interferometric scan of the compressor when set in each of the eight possible delay configurations. The packet compressor was placed in one arm of a Mach-Zehnder interferometer, and the length of the other arm was scanned with a free-space translation stage. The curves in figure 3 show the magnitude of the interference pattern generated as the reference arm length was scanned. A periodically driven piezo rod on one of the GRIN lenses on the translation stage assured a rapid interference signal at all times, and the light came from a 100 MHz mode-locked laser with 1 ps pulsewidth at a wavelength of 1.3m.

In conclusion, we have build and demonstrated a 3-stage, 8-bit optical packet compressor that compresses an incoming packet at a bit rate of 100 Mb/s to an outgoing bit rate of 100 Gb/s. Optical packet compressors, which are a subset of tunable delay lines, are necessary for ultrafast packet-switched all-optical time division multiplexed networks.

We propose a new bit-level packet-switching (BLPS) scheme for an optical multihop packet-switching shuffle network based on TDM. In the new scheme, the optical clock is separated for operation at each node and reinserted into the header before the packet leaves the node. Presently, optical pulse insertion can be done within picosecond accuracy by using either adjustable delays or a fiber stretching technique. Our scheme is particularly useful under deflection routing since the position where the clock is reinserted can be determined in a fixed manner even with a deflection of a packet. Because the scheme does not rely on a time-consuming and relatively slow look-up table, it is suitable for ultra-high speed optical networks.

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Final Remark:

This Program was terminated and therefore no Additional results were obtained

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5. Patents and Invention Disclosures

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